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Research Note

The Role of 3-D Surface Slope in a Lightness/Brightness Effect

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Adelson has shown how two patches in a 5 by 5 array of grey patches can be perceived to consist of different shades, depending on whether they are represented as a 3-D horizontal or vertical ridge. Adelson interprets the illusion in terms of the orientation of the patches with respect to the inferred illuminant. We investigated: (1) the illusion in the vertical and horizontal stimuli and added a flat (ridgeless) control stimulus; (2) stimuli of varying ridge amplitudes to examine the effect more fully. 3-D renderings of real surfaces were modelled with computer graphics and displayed to observers who used a mouse to alter the brightness of a square to match patches indicated in the stimuli. Five observers were used for the vertical, flat and horizontal stimuli, while a larger group ($n = 20$) was used for an independent design when varying ridge amplitudes. A significant effect in the flat surface demonstrates that patches lying in the same plane can have their brightnesses altered without changes in their orientation. When the surface was seen as a 3-D ridge the size of the effect was a function of 3-D slope of the surface. By measuring each patch independently we have shown that the effect changes the brightness of the two patches to differing degrees. We offer an explanation of this based on a proposed qualitative shading rule for identifying reflectance and illumination edges. Copyright © 1997 Elsevier Science Ltd

Brightness Reflectance Shape Shading

INTRODUCTION

Light arriving from a surface at the eye is the product of two primary factors: the reflectance of that surface and the illumination it is under. Lightness is the perceptual correlate of reflectance ranging on a scale from black (a surface that reflects little, if any, light) to white (a surface that reflects all or nearly all the light hitting it). Brightness‡ is the perceptual correlate of the intensity of a point in a scene ranging from dark to bright.

The perceived reflectance of surfaces remains reasonably constant under normal illumination changes. This process of lightness constancy depends not only on the retinal processes of local contrast but on other mechanisms such as those that compute shape and depth. Gilchrist (1977), Knill & Kersten (1991) and Buckley *et al.* (1994) have shown how lightness perception can be altered by changes in depth, surface curvature and binocular disparity. However, brightness perception has been presumed to remain a relatively low level mechanism. Although first suggested by Helmholtz (see Hurlbert, 1994) it is only recently that Adelson (1993, 1994) and also Schirillo & Shevell (1993) have shown that brightness, too, is influenced by higher order mechanisms.

Adelson presented a series of brightness illusions that demonstrate that perceptual organization can influence the brightness percept. We have examined in detail what Adelson described as the "corrugated plaid" shown in Fig. 1. Patches A and B have the same physical luminance yet patch A is perceived to be much darker than patch B. Local contrast may play a role in this, as the brighter patch B is surrounded by darker patches than the darker patch A. However, local contrast cannot account for all the brightness difference between the two patches as patches A′ and B′ also have the same luminance and are within exactly the same array of luminances. In this instance the shape perception has changed such that the surface is perceived with the two patches lying in the same plane and the brightness difference is much less marked. Adelson concludes from this that the brightness percept of a 3-D surface is influenced by its perceived reflectance and orientation. The vertical ridge surface may not be a suitable local contrast control as it too contains shape cues that may influence the brightness. A better surface may be the flat array of luminances shown at the right of Fig. 1. To distinguish between the surfaces we refer to them in terms of the orientation of the ridge in

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‡Some authors use the term brightness to indicate perceived illumination.

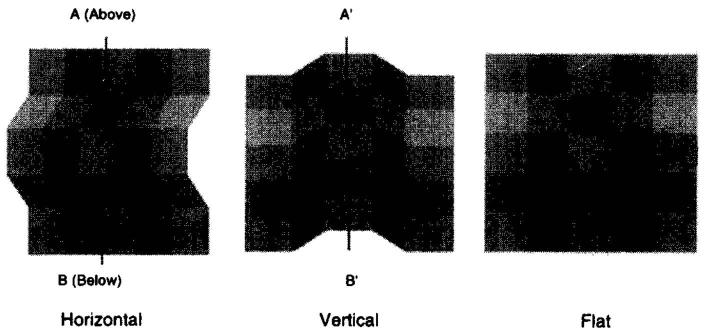

FIGURE 1. Patches A and B have the same physical luminance but patch A is perceived to be darker than patch B. Patches A′ and B′ also have the same physical luminance, but in this case the effect is greatly reduced due to the change in perceptual organization. On the right is the flat stimulus used in Experiment 1.

the two stimuli that Adelson presented, and call the additional stimulus simply the flat surface. Thus, from left to right they are the horizontal and vertical ridged surfaces and the flat surface. Adelson measured only the brightness difference between patches A and B using a nulling technique. We decided to measure the brightness percepts of patches A and B in all three surfaces independently using a match to sample technique to see if one or other of the patches accounted for most of the brightness change.

EXPERIMENT 1

Methods

Stimuli. The vertical, flat and horizontal surfaces shown in Fig. 1 were displayed on a high quality, calibrated, 8-bit monitor (Sun Microsystems Model CPD 1790) under control from a host Sun Sparc Station. Stimuli were viewed monocularly through a viewing tunnel. Alongside the stimuli was a small square probe that observers could adjust for brightness via a mouse. As the background was black, a small grey border around the probe prevented too great a contrast difference between the stimulus and the probe. The patch to be matched in the stimulus was indicated by a tiny black dot.

Observers. Five unpaid naive volunteers (three men and two women) aged between 23 and 30 yr acted as observers. They all had normal or corrected to normal vision.

Experimental design. The two factors, surface type (vertical, flat or horizontal) and patch (whether A or B*), were measured in a fully repeated measures design. Stimuli were presented twice in an order randomized between and within observers. A blank screen was presented for 2 sec in between stimuli.

Experimental procedure. Prior to the experiment observers were familiarized with the match to sample technique by using the mouse to adjust and submit their judgements on some plain example stimuli that did not resemble the experimental stimuli. Once they were familiarized with the technique the experiment proper began. Observers could take as long as they liked to adjust the probe and moved through the stimuli at their own pace. The experiment lasted around 15 min.

Results

Surface type (i.e., whether vertical, flat or horizontal) significantly affected the brightness of the two patches ($F_{2,8} = 22.60$, $P < 0.01$†). This is shown in Fig. 2. The graph shows the brightness judgements in log candles/square metre for patch A (dark grey column) and B (light grey column) for the three different surfaces. *Post hoc* difference tests (Tukey HSD) showed that although in the expected direction, the difference between patches A and B (henceforth AB difference) in the vertical surface is not significant, however, the AB difference in the other two surfaces is significant (flat: $P < 0.01$; horizontal: $P < 0.01$). Furthermore, the judgements for patch A in any of the surfaces is not significantly different from either of the other two patch A judgements. The brightness of patch B in the horizontal surface is significantly different from that of either the flat ($P < 0.01$) or vertical surfaces ($P < 0.01$). In summary, Experiment 1 demonstrated three things:

1. It replicated Adelson's effect by showing the brightness difference for patches A and B to be significantly larger in the horizontal ridged surface than in the vertical ridged surface.
2. It showed that there is a significant effect in the flat stimulus that is greater than the vertical but less than the horizontal.
3. It showed that the change in brightness takes place in patch B and that the perception of brightness of patch A remains relatively constant.

These findings prompted the following questions: What is the nature of the brightness change as the surface goes from a flat to a horizontally ridged surface? Is it the case that as soon as the surface is seen as a 3-D ridge the

*Throughout the paper we shall refer to the patches as A and B. The reader may care to remember them by A is Above and B is Below.

†Cited significance levels are those obtained applying, where necessary, conservative epsilon corrections for departures from covariance homogeneity assumptions (Howell, 1987). For brevity and simplicity, F values are cited only for significant effects.

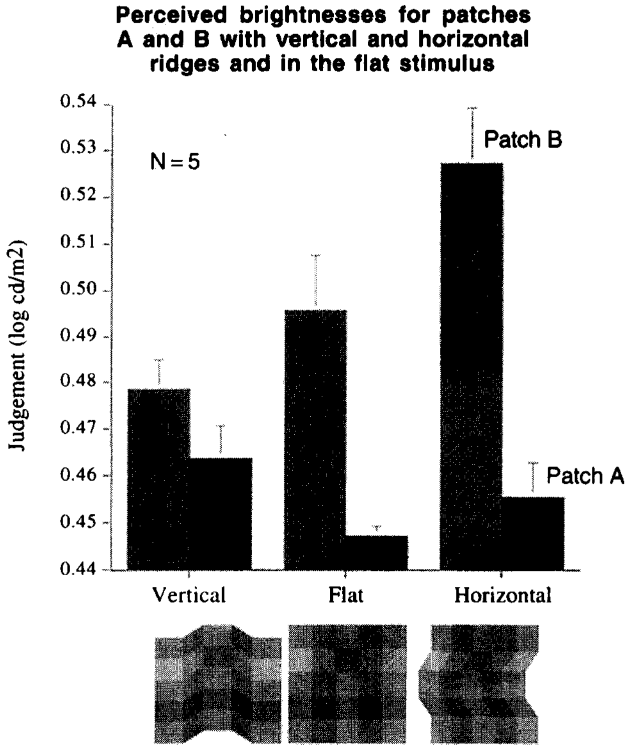

FIGURE 2. Group mean judgements ($n = 5$) for patches A and B for the vertical and horizontal ridged surfaces and the flat surface. The error bars are $\pm$1S.E.

brightness changes dramatically, as in a step function, or does it change gradually as the surface becomes more ridged? Experiment 2 sought to investigate how the AB effect changed as the 3-D slope of the surface was changed from the flat surface into the horizontal ridge.

EXPERIMENT 2

Experiment 2 differed from Experiment 1 in two ways. First of all the stimuli were perspective projections of 3-D rendered surfaces and secondly a different experimental design was employed. The reason for this was that we felt there was a tendency to perceive the flat surface as a singular* view of a ridged surface after many viewings of ridged surfaces. So that this would not be a problem we designed the experiment in three phases with independent groups as described below.

Methods

Stimuli. Whereas the stimuli in Experiment 1 had simply been created to be replicas of Adelson's stimuli, in Experiment 2 we used perspective projections of 3-D rendered surfaces in an attempt to better approximate natural images and hence investigate real world perception [Fig. 3(a)]. Surfaces were rendered with an illumination model that took into consideration ambient light and how much the surface reflected it, a point light source and how much the surface reflected this scaled by a factor accounting for the surface's attitude to the illuminant direction (details given in the legend to Fig. 3).

A perspective projection of the horizontal surface, with rows 2 and 4 inclined at 45 deg to the other rows, was rendered and the grey levels obtained used for the remaining surfaces, where rows 2 and 4 were inclined at 0, 15 and 30 deg [see Fig. 3(b)]. In modelling a real surface it is impossible to prevent some minor factors changing between stimuli. For instance, in the four stimuli the top and bottom rows remain unchanged but as the 3-D surface slope increases the second and fourth rows naturally decrease in vertical height in the image plane. Such changes were allowed to happen as we placed more importance on modelling real 3-D surfaces than controlling for the vertical height or changes in other factors which were natural consequences of changing the 3-D shape of a perspectively projected object.

Observers. 20 unpaid naive volunteers (9 men and 11 women) aged between 20 and 35 yr acted as observers. All observers had normal or corrected to normal vision.

Experimental design and procedure. Experiment 2 was carried out in an analogous manner to Experiment 1, except that initially independent groups of observers viewed each stimulus (i.e., one group of five observers for each of the four 3-D slopes). The reason for this was that we felt there was a tendency to perceive the flat surface as a singular view of a ridged surface after many viewings of ridged surfaces. Thus, observers in the flat (0 deg surface slope) group had never seen any of the other stimuli before. This is also the case for the other independent groups e.g. observers in the 45 deg slope group viewed that stimulus before any of the others. Observers were also trained on stimuli with the same geometry but with random luminances. Thus observers in the flat group had a flat stimulus with random† shades for training, observers in the 15 deg slope group had a 15 deg surface slope stimulus with random shades to train on and so on. After observers in a given group had seen the appropriate stimuli they then judged the remaining three surface slopes in a repeated design before finally submitting a further set of judgements on their original stimuli. In other words the experiment was conducted in three phases. In phase 1, observers judged their assigned stimuli, for example flat (0 deg surface slope), they then judged all the remaining stimuli (15, 30 and 45 deg surface slopes) in the second phase. In the third and final stage observers again judged the same stimuli from the first phase, in this case the flat stimuli. The experiment lasted about 20 min.

Results

Figure 4 shows observers judgements before and after viewing the other stimuli i.e., their judgements from phases 1 and 3 of the experiment. There are no significant differences for the size of AB effect whether the stimulus

*We use the term singular view to mean that the horizontal ridged surface may have the same projection at the eye as a flat surface if viewed from a particular station point.

†A range of random stimuli were generated. Then one that had no contrast or shading effects similar to the experimental stimuli was chosen.

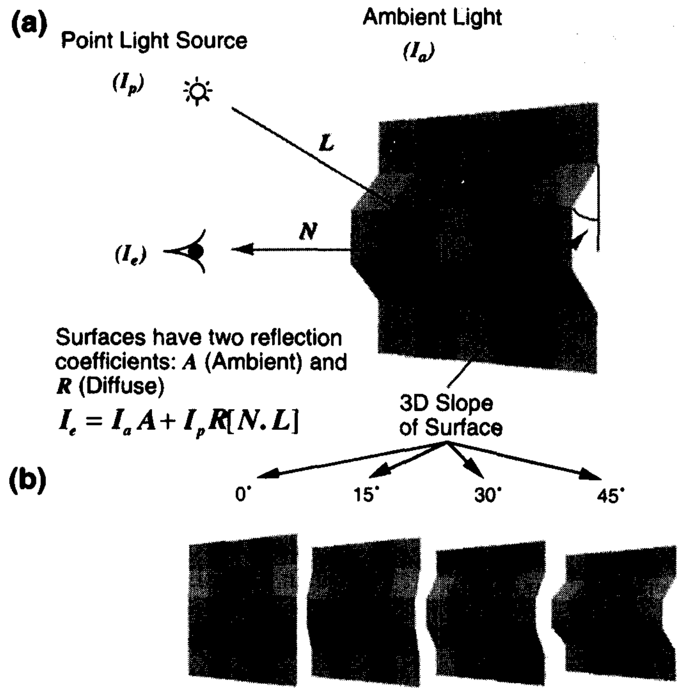

FIGURE 3. (a) In Experiment 2 the stimuli were modelled as rendered, perspective projections of real 3D surfaces. The illumination model took account of the amount of ambient light in the environment and the degree to which surfaces reflected it. Also taken into account was a point source of light and the degree to which surfaces reflected that scaled by the attitude of the surface to the point light source. The values used in our model were: $I_a = I_p = 1.0$, $A = 0.4$, $R_1 = 0.40$, $R_2 = 0.25$, $R_3 = 0.12$, $L = [0.67, -0.47, -0.57]$ (z axis coming out of the page). Surfaces were generated by creating a flat surface in frontoparallel (xy) plane, then rows 2 and 4 were slanted by the desired amount (0–45 deg, the surface shown has 45 deg slope) and then the whole surface was rotated around the y-axis by approximately 40 deg. N shown in the figure has a value of $[-0.64, 0, 0.76]$. (b) The four experimental stimuli used.

was viewed before or after the other stimuli. So for observers in the flat group, the brightness of the patches did not alter if they viewed this type of stimulus for the very first time compared to if they had already seen the ridged stimuli. The remaining analysis, therefore, uses all the data regardless of which phase of the experiment they came from.

As in Experiment 1, 3-D slope significantly affected the brightness of the patches ($F_{3,32} = 5.50$, $P < 0.01$). This is shown in Fig. 5. The graph shows the brightness judgements for patches A and B as the 3-D slope of the surface was increased. The AB difference was significant for all surfaces [$P < 0.05$ (flat); $P < 0.01$ (15, 30 and 45 deg slopes)]. Also, as in Experiment 1 there are no differences between patch A means and it is patch B that is perceived to become brighter with increasing slope.

To summarize, Experiment 2 showed that:

1. There is no significant difference in the size of the effect whether or not a given stimulus was viewed for the first time or was seen after viewing the other stimuli.
2. Varying the 3-D slope of the surface increased the brightness difference between patches A and B.
3. The brightness change in patch B is a function of the 3-D slope: it does not suddenly change to a new level as in a step function as soon as the surface is perceived to be a ridge.
4. The brightness differences were accounted for by changes in patch B, with no significant differences between any of the patch A means.

DISCUSSION

The two main results that must be accounted for are: why does 3-D slope affect surface brightness and why in these stimuli does it affect only patch B?

Figure 6 attempts to interpret the 3-D slope effect. Suppose that the visual system knows something about the physics of image formation. It knows that the intensity of photoreceptor stimulation is a function of three factors: the intensity of the illumination in the environment, the reflectance of the viewed surface, and the orientation of that surface with respect to the light source. Figure 6 summarizes Experiment 2: the intensity at the eye (I_e) has been kept constant whilst the surface normals changed. To accommodate this either perceived illumination (I_p) or surface reflectance (R) must change. It is unlikely that perceived illumination would be adjusted as there is evidence in the stimuli to the contrary. This comes from the top, middle and bottom rows which appear to consist of the same reflectances in

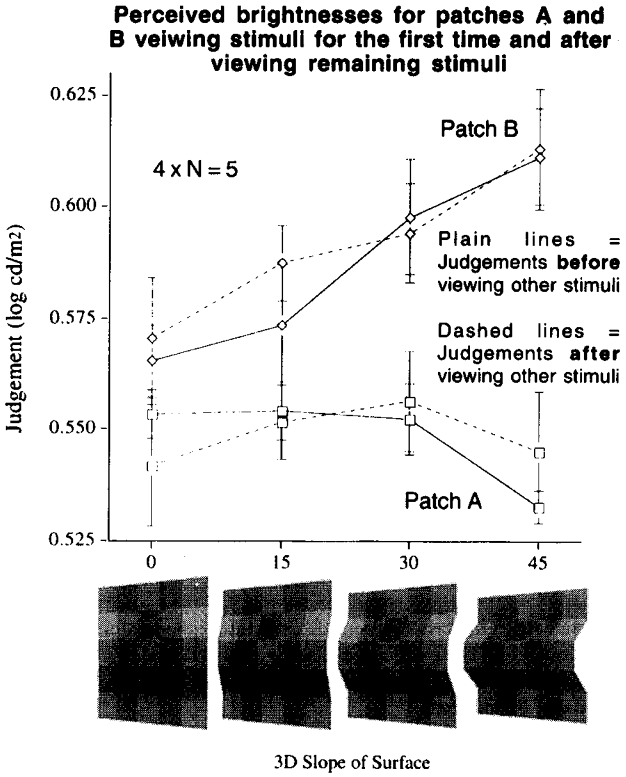

FIGURE 4. Group mean judgements (four groups of $n = 5$) for patches A and B before (phase 1) and after (phase 3) viewing the other surfaces.

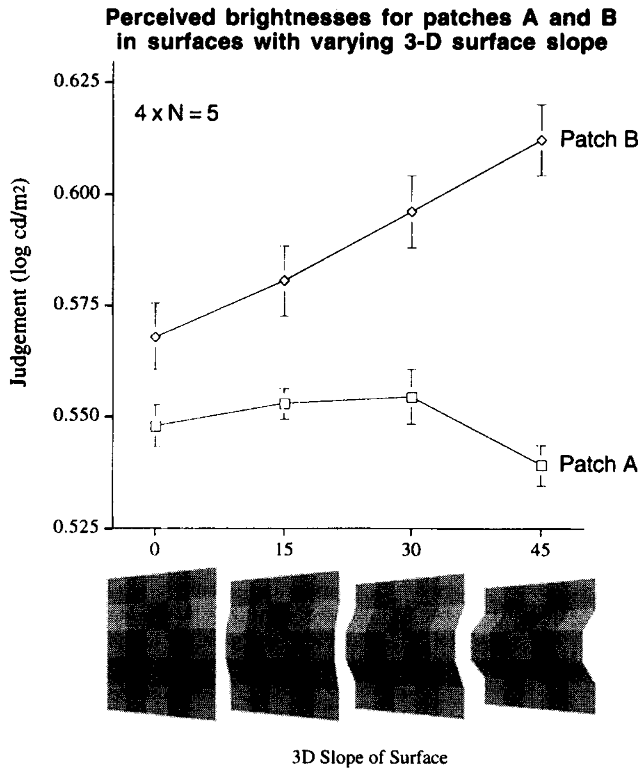

FIGURE 5. Group mean judgements (four groups of $n = 5$) for patches A and B from all phases of the experiment.

the same orientation in each stimulus. Any change in perceived illumination would affect the brightness of these rows. Casual observations suggest this is not the case. Surface reflectance would, therefore, seem the most likely candidate to be adjusted and account for the change in brightness. Adelson's initial demonstration showed that perceived reflectance appeared to influence brightness. Possibly the visual system adjusts the perceived reflectance of patch B to accommodate the changes in surface slope and this then influences the brightness. But why does this adjustment happen only to patch B?

To address this question first consider the problem for the visual system: it is presented with a 3-D array of luminances and it has to determine for any pair of patches if the difference in luminance between them is a difference due to reflection or due to illumination. Any two neighbouring patches examined in isolation are fairly uninformative. There is little to differentiate whether they are the same reflectance under the same illumination conditions or the same reflectance under different illumination conditions. However, there is considerably more information available in quadrants of patches. One possible explanation of why patch B is affected but not patch A is that it is clearly defined as a surface sharing the same reflectance as its vertical neighbours but shaded. It obeys what we call the "qualitative shading rules" shown in Fig. 7. As long as the qualitative relationships of $x{:}y$ representing the reflectance edge and $x{:}x'$ representing the illumination edge are maintained for $x'{:}y'$ and $y{:}y'$ then patch B is seen as shaded. Another way of putting this is to say that the probability of patch B having the same reflectance as the patch above it but in shade is greatly increased by having neighbouring patches that exhibit similar luminance relationships. Furthermore we can describe the junction at the centre of four patches as having ratio invariance.

Although in this instance, patch B is literally "in the

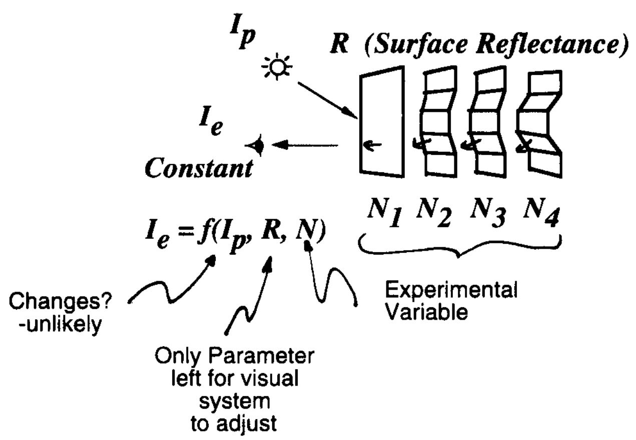

FIGURE 6. A possible interpretation of the visual system's task in Experiment 2. The visual system knows that light reaching the eye is a function of the intensity of the light source, surface reflectance, and surface orientation. In Experiment 2, the surface orientation was varied whilst keeping the intensity of light at the eye the same. To accommodate this we suggest that the visual system adjusts the perceived surface reflectance. See text for details.

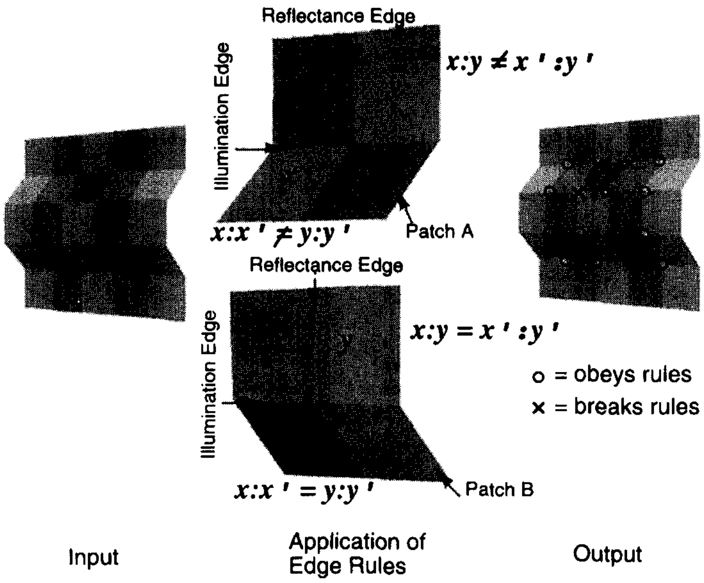

FIGURE 7. The qualitative shading rule interpretation of why the effect changes the brightness of patch B rather than patch A. The horizontal ridged surface shown on the left is the input for the computation. The qualitative shading rule described in the centre is applied at each junction and the result shown on the right. Patch A is singular, in that unlike all the other patches, no relationships with its neighbours can be inferred.

shade" the shading rules should also apply to patches that are "in the light". For instance, all the patches in the second row of the stimulus with the exception of patch A obey the qualitative shading rules. Therefore, as far as the qualitative shading rules are concerned the term "shaded" simply refers to a patch that can be interpreted as having the same reflectance as one of its neighbours. However, that patch could be either "in the shade", as in patch B, or "in the light", for example the first patch in the second row. We shall use this as our definition of the word "shaded", so the reader should be aware that it does not always refer to a patch in shade but can refer to a patch in light as well.

We call these rules "qualitative" because we have created stimuli which do not preserve the $x{:}y = x'{:}y'$ and $x{:}x' = y{:}y'$ relationships quantitatively and yet the Adelson effect can still be observed as long as the relationships are roughly satisfied. Examining when the qualitative rules break down is a topic for future research. The approach of using qualitative shading rules to determine when a brightness effect occurs is novel to the best of our knowledge, although similar techniques for recovering reflectance and illumination are described by Sinha & Adelson (1993) and for detecting transparency by Metelli (1985).

If all the grey-level junctions are labelled (see Fig. 7) to show which ones obey and which ones break the qualitative shading rules, then patch A emerges as a unique patch in that it does not exhibit an interpretable shading relationship with any of its neighbouring patches under the qualitative shading rules. The visual system then possibly discards patch A as legitimate input to the type of computations that it carries out on patch B. This could be the reason why the observed brightness changes occur only for patch B.

The luminance ratios that define the shading rules are as equally well observed by patch B in the vertical surface as in the horizontal surface yet the AB effect is greatly reduced in this case—why? Our explanation relies on the fact that as we transform the horizontal surface into the vertical one, what were illumination edges in the horizontal now become reflectance edges in the vertical (at least for the local area around patch B). Similarly what were reflectance edges in the horizontal become illumination edges in the vertical. Therefore, the shape perception must be interpreted in conjunction with the luminance ratios. Thus patch B is no longer an in-shade patch liable to some kind of brightness adjustment but is seen in the same plane as patch A and linked only by reflectance edges (Fig. 8).

The final result to account for is: why was there an effect in the flat surface? There seem to be two main explanations. The first is that, although a flat surface, the arrangement of luminances has structure: it has not been set arbitrarily. It is possible that the arrangement of luminances could result in the flat surface being seen as a singular view of either the horizontal or vertical surfaces. Forced with these two equally possible interpretations the visual system assigns a brightness to patch B intermediate to that which it would assign to either the horizontal or vertical cases (Fig. 8). Analogous interpretations follow for considering that the flat surface may have properties of transparency. Either the fourth row down could be considered transparent (or possibly a cast shadow) or the second and fourth columns could be considered transparent. Note how the first of these interpretations relates to the shading in the horizontal

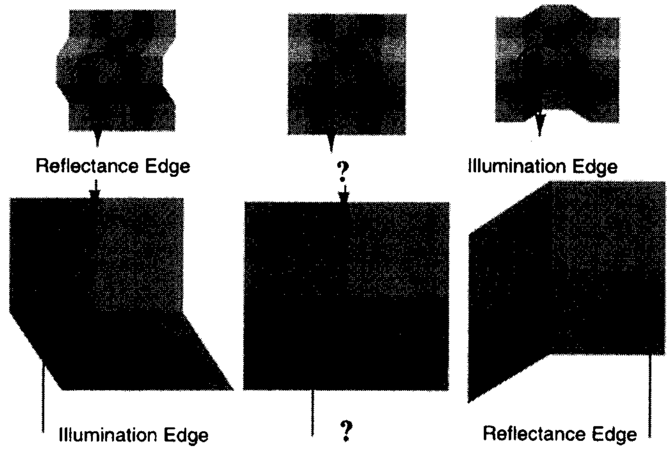

FIGURE 8. The differences in interpretation for the horizontal and vertically ridged surfaces and the flat surface. The reflectance edges in the horizontal ridged stimulus become illumination edges in the vertical ridged stimulus and vice versa. However, which edges are reflectance or illumination in the flat surface is ambiguous.

surface and the second relates to the shading in the vertical.

The second explanation is that the AB effect in the flat case is due solely to local contrast. In this case the interpretation for the AB effect in the horizontal and vertical ridged surfaces is that the factors that increased the AB effect in the horizontal surface also work in the vertical surface. However, in this instance they act to reduce the effect rather than enhance it as was the case in the horizontal. Which of these two interpretations is more likely to be correct is one possible avenue for further research.

The relationship between brightness and lightness in stimuli such as the ones we have been using is complex. Even in the 2-D literature there has been a tendency to confuse the two terms. We term Adelson's effect a "brightness/lightness effect" in recognition of the fact that both processes are involved. The perceived lightness of patch B changes from the vertical ridged stimulus to the horizontal ridged stimulus and our shading rule explanation also relied on knowing the reflectance relationships between patches and therefore it cannot be a purely brightness effect. However, changes in perceived lightness cannot on their own account for the effect because there are also conflicting cues in the stimuli that lightness is not changing. Consider patch B in the varying 3-D slope stimuli. Patch B appears to be the same reflectance as its vertical neighbours. Although patch B becomes brighter with increasing 3-D slope its vertical neighbours appear* to remain the same brightness and lightness. If patch B is seen as the same reflectance as neighbouring patches that do not change in lightness, then it cannot be a purely lightness effect either.

This confusion might arise from the fact that lightness or brightness descriptions typically allow for only one perceptual value to be assigned to a point in an image. Perceptual experience dictates otherwise. Patch B in the horizontal ridged stimulus is seen as having both a lightness that is the same as its vertical neighbours and an illumination difference. An important area for future research lies in developing ways of describing the multidimensional perceptual experience of stimuli such as the ones presented here.

In summary, we have extended Adelson's illusion to the flat case and to surfaces with varying 3-D slopes and shown how the effect changes in these cases. Our results further generalize Adelson's effect and reveal some of the processes for the cue combination of brightness and shape in simple 3-D scenes.

*At least in the opinion of the authors, however, this has not been measured experimentally.

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